HELIUM: Origin, Use, Supply and Demand

by Jon E. Spencer

INTRODUCTION

Most people give little thought to helium gas except when it is used to inflate children's balloons at circuses or parades, or when its properties are revealed in a high school chemistry class. Helium is actually a unique and indispensable natural resource that is crucial for many industrial and research activites. The following narrative describes the geologic occurrence and physical properties of helium, outlines the history of its discovery and development as a natural resource, and examines possible future uses of helium as well as the consequences of its depletion.

Several natural gas fields in the United States contain most of the world's known helium reserves. Most natural gas contains small amounts of helium which, unless extracted from the natural gas, are lost to the atmosphere when the gas is burned. Roughly 14 billion cubic feet of helium (about one-tenth of a cubic mile) are contained in natural gas produced domestically each year. About one billion cubic feet of this helium is extracted and sold commercially, while the rest is dissipated into the atmosphere. The atmosphere is a virtually limitless and renewable source of helium, but the cost of atmospheric recovery of helium is high due to the increased energy requirement for extraction from such a dilute source (five parts helium per million parts air). It is estimated that it would cost $2,000-$6,000 to extract a thousand cubic feet of helium from the atmosphere, compared to less than $13 for extraction of the same quantity from natural gas containing more than 0.3 percent helium (3,000 parts per million) (Peach, 1981).

The importance of helium to industry and scientific research, and its possible importance to future energy-related industries, has long been recognized. As a result, efforts have been made to extract helium from natural gas and to pump it underground into depleted natural gas reservoirs where it can be stored indefinitely. About 40 billion cubic feet of helium have been stored in the Cliffside reservoir in northern Texas by the U.S. Bureau of Mines before federal funding for helium extraction and storage was terminated in 1973 for budgetary reasons. Despite legislative attempts to revive the helium conservation program, it is not likely to be renewed in the near future. At current rates of helium production and discovery, the world's underground helium reserves will be depleted by the middle of the 21st century. However, as helium-intensive energy technologies become practical and helium reserves are depleted, the debate over the merits of federally funded helium conservation will intensify. Advanced electric power generation, storage, and

The Goodyear "blimp"—one of four lighter-than-air craft in the Goodyear fleet today. Since 1917 Goodyear has built more than 300 helium-filled dirigibles; 60 of these have been used as commercial airships which also promote community activities and public service throughout the U.S. and Europe. A "blimp" is 192 feet long, 59 feet high and weighs 9,500 pounds when empty; it travels 35-50 mph at heights of 1,000-10,000 feet, and can carry a maximum load of 2,820 pounds. Photo courtesy of Goodyear Aerospace Corporation.

transmission devices, now in research and development, may require large amounts of helium in the future.

ORIGIN OF HELIUM

Helium is the second element on the periodic table of the chemical elements and is the second most abundant element in the universe. Only hydrogen, the first element on the periodic table, is more abundant. The sun's energy is derived almost entirely from fusion of hydrogen nuclei into helium nuclei. In fact, the sun and stars can be regarded as enormous helium factories.

On Earth where temperatures and pressures are far too low for nuclear fusion, much smaller amounts of helium are produced by radioactive decay of uranium and thorium. A single atom of uranium 238, the most abundant isotope of uranium, produces eight helium nuclei during its long decay into lead. Over millions of years, trillions of cubic feet of helium have been produced by radioactive decay of uranium and thorium in the Earth's crust. Helium produced in the Earth is initially trapped in the rocks and minerals in which it is formed. Large amounts of helium eventually escape into the atmosphere, and from there escape into outer space. Smaller amounts, however, accumulate in underground geologic reservoirs. Both natural gas and helium accumulate in porous and permeable sedimentary rocks overlain by impermeable strata, although the two types of gas are derived from different sources. Helium is derived from rocks rich in uranium, whereas natural gas is derived from rocks rich in organic matter. The two types of gas are typically found together in underground reservoirs, although the relative concentration of each varies greatly because of differences in the concentrations of uranium and organic matter in source rocks.

DISCOVERY AND EARLY USES OF HELIUM

Helium was discovered simultaneously by British astronomer Norman Lockyer and French astronomer Pierre Janssen in 1868. Lockyer noticed that a bright yellow spectral line which appeared in light emitted from the sun's corona was an element not known on Earth. He later named the element "helium", from the Greek word for sun, helios (Seibel, 1968).

Twenty-three years later (1895) in a London laboratory, professor William Ramsay dissolved one gram of the uranium-bearing mineral cleveite in acid and obtained a gas which he purified and examined spectroscopically. Because he did not recognize the gas, Ramsay sent a sample to Sir William Crooke, a noted spectroscopist, who identified it as helium. Within a few years of this discovery, helium had been found in a variety of uranium and thorium-bearing minerals, and in the air.

In 1905 Dr. H.P. Cady of the University of Kansas analyzed gas from a natural gas well in Dexter, Kansas, and discovered that it contained almost two percent helium. Afterward, Cady and his colleague, Dr. D.F. McFarland, analyzed 44 samples from natural gas wells in Kansas, and recognized the widespread occurrence of helium in natural gas. Cady spoke wisely when he stated: " . . . helium is no longer a rare element, but a very common element, existing in goodly quantity for the uses that are as yet to be found for it" (Seibel, 1968).

Techniques for large-scale extraction of helium from natural gas were developed for military purposes. The Germans made much use of hydrogen-filled zeppelins during World War I. These lighter-than-air vehicles could drop bombs from 16,000 feet, which was higher than airplanes of the time could fly. Using rockets that exploded in a shower of sparks, the British learned that a single spark could send a zeppelin crashing to the ground as flaming wreckage. The advantages of using nonflammable helium became obvious, and, by 1917, the U.S. Bureau of Mines was financing research and development of helium-extraction plants. The first significant quantities of helium were not available until the end of World War I. However, research and development continued, and large quantities of helium were available for use as a lifting gas in airships during World War II. Many new uses for helium, some of them related to national defense, were found during the years immediately following the second world war.

HELIUM CONSERVATION

In a 1954 report prepared for the U.S. Bureau of Mines, the need for helium conservation was addressed:

> Since the helium occurs in mixture with the natural gas . . . present reserves of helium are being dissipated every day as a part of the large natural gas deliveries to the fuels markets. . . . The alternatives to permitting the rapid disappearance of the helium reserves is to institute an active program for conservation of a large quantity of helium as a national asset for the more distant future [Henrie and others, 1978].

Following this and later studies of helium supply and demand, the federal government passed the Helium Act Amendments of 1960. This act authorized the Bureau of Mines to enter into contracts for the purchase of helium during the following 25 years.

Shortly after the passage of the Helium Act Amendments, several companies constructed helium extraction plants and began selling helium to the U.S. Bureau of Mines under contract agreements. The Bureau pumped the helium into the Bush Dome at its Cliffside-field subsurface geologic storage reservoir near Amarillo, Texas. The helium was injected into the center of the domal-shaped reservoir rock, while natural gas was pumped from the margins. When helium purchases were terminated in 1973, 36 billion cubic feet of helium had been extracted and stored at a cost of more than $300 million.

HELIUM PROPERTIES AND USES

Helium has a number of unique properties that make it useful in a variety of applications. Originally used only as a lighter-than-air lifting gas, it now has over 75 uses, most of which were developed after World War II. Three major uses—cryogenics, heliarc welding, and purging and pressurizing—account for about two-thirds of domestic helium uses (Figure 1; Table 1).

The following description of helium uses is based on reports by Davis (1980), Henrie and others (1978), and Midwest Research Institute (1977):
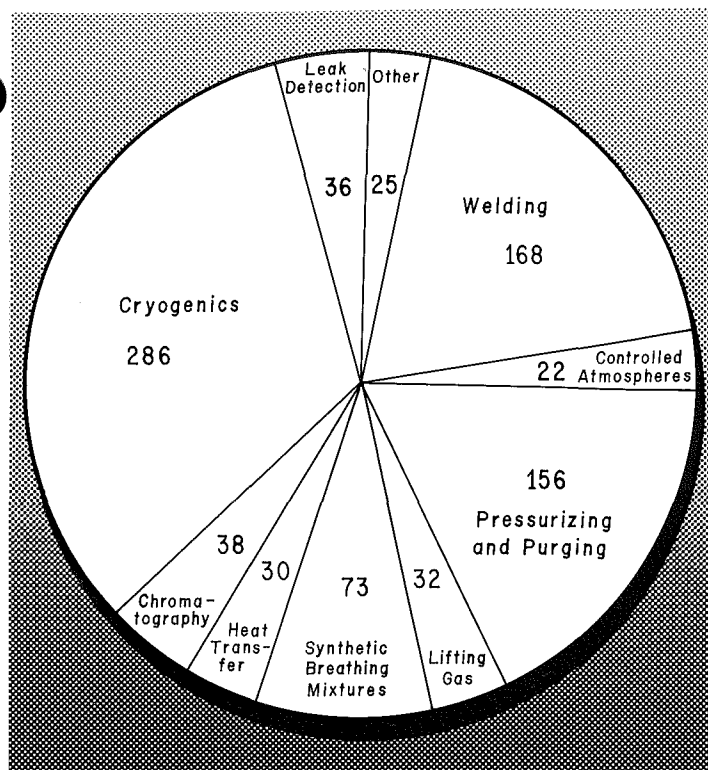
Figure 1. Uses of helium in the United States in 1981, based on U.S. Bureau of Mines data (Tully, 1982). Total helium used in the U.S. was about 866 million cubic feet.

Cryogenics

Cryogenics refers to scientific and engineering work performed at temperatures below about $-232°F$ ($-153°C$) and above absolute zero, $-459°F$ ($-273°C$). [It is theoretically impossible to reach absolute zero, although scientists have come extremely close]. Helium is the only known substance that remains liquid at extremely low temperatures and can be used as a coolant to achieve and maintain temperatures within $14°C$ ($25°F$) of absolute zero. [Hydrogen, the closest competitor of helium, freezes at $-259°C$ ($-434°F$)].

At temperatures within a few degrees of absolute zero, some substances become superconductive, a condition in which the resistance to the flow of electricity is zero. Achieving superconducting temperatures is one of the most important uses of helium, although some materials become superconductive above the freezing temperature of hydrogen. Superconducting electromagnets, for example, produce intense magnetic fields at about one-tenth the operating cost of conventional electromagnets. A major use of superconducting magnets at present is in particle physics research. Research is being done to develop superconducting magnets for magnetic-confinement fusion power generation, MDH (magnetohydrodynamic) power generation and magnetic electricity-storage devices. Superconducting generators and motors are also being studied. Widespread commercial use of these technologies is unlikely for at least the next 20-30 years.

Superconductivity is also important for a number of electronic instruments, including masers (microwave equivalent of lasers) for microwave communications with satellites, highly sensitive infrared detectors for military observation satellites and astrophysical research, and NMR (nuclear-magnetic resonance) imaging, a technique that may replace X-rays in medical applications. Research on superconducting computer elements, and a whole variety of scientific instruments based on superconductivity, could lead to dozens of new uses for helium as a refrigerant.

Welding

Many metals, such as aluminum, magnesium, and stainless steel, cannot be welded together by arc welding under normal atmospheric conditions because the molten metal reacts with oxygen and nitrogen in the atmosphere. These metals can be welded, however, by use of inert-gas-shielded arc welding. In this technique, the electrical arc providing heat to the metal is surrounded by a jet of inert gas that shields the arc and the metal from reactive gases in the atmosphere. Helium is preferred over argon in most situations because it improves weld penetration and appearance, and allows greater welding speed.

Pressurizing and Purging

Helium has a number of properties, including chemical inertness, very low boiling point, low solubility, and low density, that make it ideal for pressurizing and purging such things as rocket fuel tanks. NASA has been the primary

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
WORLD PRODUCTION											
United States	760	647	577	627	647	699	745	808	947	1,001	1,062
Rest of World	90	90	112	122	132	140	146	146	149	149	181
Total World Production*	850	737	689	749	779	839	891	954	1,096	1,150	1,243
U.S. DEMAND PATTERN											
Purging and pressurizing	271	219	164	180	149	116	109	114	140	146	147
Controlled atmospheres	78	63	46	52	53	63	16	19	21	21	21
Welding	72	58	52	57	91	106	97	102	151	157	158
Lifting gas	51	41	23	25	11	11	23	25	29	30	30
Leak detection	48	38	32	36	30	37	25	25	32	34	34
Cryogenics	112	90	104	113	123	127	207	223	258	268	270
Chromatography	16	13	19	21	21	21	25	25	33	35	36
Heat transfer	10	8	9	10	16	37	24	25	27	28	28
Breathing mixtures	5	5	14	16	27	32	55	57	65	68	69
Other uses	7	7	7	5	9	20	20	19	23	24	24
Total U.S. Demand*	670	542	470	515	530	570	601	634	779	811	817

*Estimated Amounts

Table 1. U.S. and world production of helium, and U.S. demand pattern, 1969-1979 (Davis, 1980).

consumer of helium for this purpose. Helium is the only gas that can be used to pressurize liquid hydrogen in rocket fuel tanks because all other gases freeze at liquid hydrogen temperatures.

Breathing Mixtures

Compared to other gases, helium is relatively insoluble in liquids and, therefore, relatively insoluble in human blood. Deep-sea divers, using helium-oxygen breathing mixtures at depths greater than 100-200 feet, can return to the surface much more rapidly than divers using conventional nitrogen-oxygen breathing mixtures. Because nitrogen is more soluble in blood than helium, it will form bubbles upon rapid decompression, a potentially fatal condition known as the "bends." Helium is widely used for breathing mixtures by companies involved in offshore oil and gas exploration and production, and by U.S. Navy divers.

Chromatography

Gas chromatography is an analytic process by which volatile substances can be separated into individual components by flowing the sample and a carrier gas through an adsorbant medium. Helium is preferred as a carrier gas in most cases because of its high thermal conductivity, low solubility, and chemical inertness. About 80 percent of the 40,000 chromatographs in operation today employ helium as a carrier gas.

Leak Detection

Helium is used to detect and locate minute leaks in pressure and vacuum systems because it has the highest diffusion coefficient of any gas (i.e., the ability to go through microscopic holes and to diffuse throughout a medium), and it can be easily detected. Helium detectors are now sufficiently sensitive to detect a leak with a flow rate such that one tablespoon of helium would take 100,000 years to pass through an opening. Leak detection capability has been of great value to the semiconductor, nuclear, aerospace, refrigeration, and food canning industries, as well as to many scientific laboratories.

Lifting Gas

The dangers of using hydrogen as a lifting gas are exemplified by the explosive fire that destroyed the hydrogen-filled dirigible "Hindenberg" in 1937. Helium has 93 percent of the lifting power of hydrogen, but no explosive potential. Primary uses of helium as a lifting gas include weather balloons, upper-atmosphere research balloons, blimps used for advertising (see cover photo), and balloons used to transport logs from inaccessible logging areas to collection points.

Heat Transfer

Helium is an ideal heat transfer medium because it has a high thermal conductivity and high heat capacity, and is chemically inert. Helium is used as the primary coolant in some gas-cooled nuclear reactors. In addition to the properties mentioned above, the high resistance of helium to neutron bombardment makes it ideally suited for this application. Several high-temperature, gas-cooled nuclear reactors (HTGRs) in this country and Europe have demonstrated the benefits of this design over conventional water

or steam-cooled reactors. The Fort St. Vrain Nuclear Generating Station, a 330 megawatt HTGR in Colorado, is this country's only large helium-cooled reactor. Unlike conventional water-cooled reactors, helium-cooled HTGRs use large, massive graphite cores to contain the nuclear fuel. In the event of a total coolant loss, serious damage and potential meltdown of the core of a water-cooled reactor begins to occur within 1-2 minutes, whereas at least 10 hours is required to reach critical temperatures in a helium-cooled HTGR. This feature of HTGRs, plus their greater energy efficiency and reduced nuclear waste generation, should make them attractive to public utilities if and when the utilities resume ordering nuclear power plants (Agnew, 1981).

Controlled Atmospheres

A helium atmosphere is used as an inert environment for the growth of high-purity crystals needed by a variety of industries. Germanium and silicon crystals grown in helium atmospheres are used in transistors and other semiconductors, and other crystals with special optical properties are grown for use in lasers and masers. Helium is also used for the purification of rare metals, such as titanium, and in super-high-speed wind tunnels.

Other Uses

There are numerous other small-volume uses of helium which include medical applications, where helium is used as a carrier gas for potentially explosive anesthetics, and for diagnosis and treatment of respiratory disorders. Other miscellaneous uses include lasers, gas-lubricated bearings and high-speed gyroscopes, particle physics research, and improved light sources.

FUTURE SUPPLY AND DEMAND

With the exception of helium stored in the Cliffside reservoir, almost all of the world's economic helium reserves are mixed with natural gas, and most of these helium-rich natural gas fields are in four states (Texas, Oklahoma, Kansas, and Wyoming). Gas from these fields contains about one-half percent helium, while most other gas fields around the world contain helium in considerably lower concentrations. "Economic", or helium-rich natural gas, is generally considered to be gas with more than 0.3 percent helium. Helium can be recovered from natural gas with less than 0.3 percent helium, but the energy requirements, and therefore the costs, are greater.

Because the demand for helium is small relative to the amount of helium pumped from the ground, helium is not generally extracted from helium-rich natural gas, and is lost to the atmosphere when the gas is burned. As long as excess helium is being pumped from underground natural gas fields, there will be no shortage of helium. When demand can no longer be met by extracting helium from natural gas in pipelines, helium will be available from the Bureau of Mines' helium reservoir. At present rates of helium consumption (about one billion cubic feet per year), helium in the federal storage reservoir could supply helium needs for 35-40 years.

Estimating the present volume of total helium reserves and the rate of helium depletion is subject to many uncertainties. Volumes of known natural gas and helium reserves are only approximately known, and estimates of
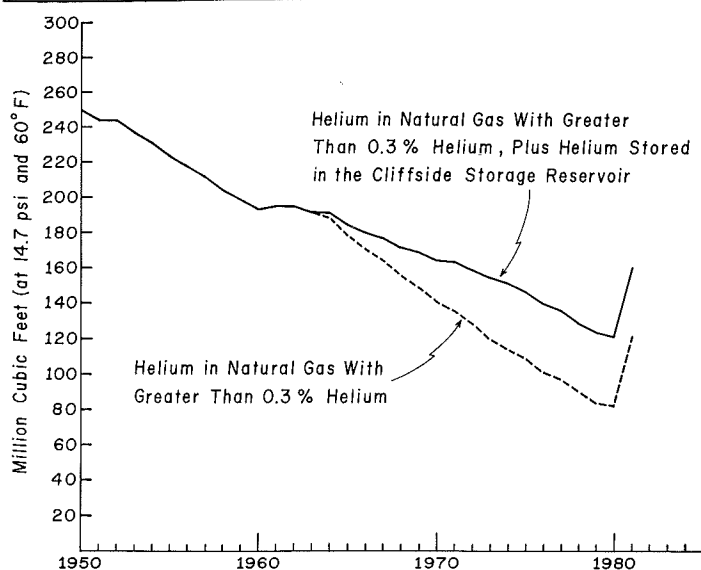
Figure 2. Measured helium reserves in helium-rich natural gas (>0.3 percent helium), in the United States and in the Cliffside storage reservoir (Hertweck and Miller, 1983). Note that new discoveries have not kept up with depletion of producing gas fields. The large increase in helium reserves in 1981 is due to increased estimates of the amount of helium in the Tip Top field of southwestern Wyoming.

the size and helium content of undiscovered natural gas fields are highly speculative. The U.S. Bureau of Mines reported that U.S. helium reserves, as of January 1, 1979, totaled 743 billion cubic feet. This amount includes 141 billion cubic feet of "measured" (proved) and "indicated" (probable) reserves, 40 billion cubic feet in the Cliffside reservoir, and 562 billion cubic feet of "hypothetical" (possible) and "speculative" reserves (Davis, 1980). It is predicted that the *helium-rich* natural gas reserves in the U.S. will be depleted within about 30 years, based on rates of discovery and depletion of proven helium-rich natural gas fields (Figure 2; Cook, 1979). *Helium-lean* natural gas will become an economic source of helium at this time, although the cost of recovery will be substantially larger. By the year 2030, the world's natural gas reserves might be nearing exhaustion. At this point, the only remaining sources of helium will be stored helium, and the atmosphere.

Estimating the future demand for helium is also subject to considerable uncertainty. Millions of dollars are spent each year on research and development of helium-intensive energy technologies that, if developed on a large scale, could involve the consumption of large amounts of helium in the early part of the next century. It is ironic that there may be little helium left if and when new helium-intensive, energy-producing technologies become feasible, and conventional energy sources such as natural gas near depletion.

CONCLUSION

The question of helium conservation is well-stated by Cook (1979): "How [do we] decide whether it is worthwhile to pay a present tangible and calculable cost to conserve a finite resource for uncertain and partly intangible benefits that will accrue mainly to future generations?" Efforts during the past decade to revive the helium conservation program have been unsuccessful.

Given current economic problems, it is unlikely that the program will be revived in the near future.

Fortunately, a substantial amount of helium can be conserved without the large expenditure of tax dollars that would be required to revive the helium extraction plants which supply the federal storage reservoir. The Tip Top natural gas field in Wyoming is estimated to contain at least 54 billion cubic feet of helium at a concentration of 0.8 percent (Clark, 1981). Mobil Oil Corporation may soon begin producing natural gas from this field, which will result in loss of its helium reserves. Ninety-five percent of these reserves lie under federal land, and thus, the federal government could require extraction and storage of helium from this gas field, or it could prohibit production until the helium is needed.

As long as our technological civilization exists, helium is likely to be a useful and, in some cases, essential resource. If energy becomes cheap and plentiful in the future, helium can always be extracted from the atmosphere. Should energy become more expensive, as it may if fossil fuels are depleted and other energy sources prove to be costly, helium will be prohibitively expensive for all but the most crucial uses. Given the many unique and outstanding properties of helium, it might be a wise and practical investment in our future to conserve this valuable resource while it is relatively inexpensive to do so.

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LOCAL EVENTS

On October 21, 1983, there will be a symposium on Land Subsidence in Phoenix. Contact Lewis Scott, Arizona Consulting Engineers Association, Suite 111, 3625 N. 16th St., Phoenix, AZ 85016; 602/968-8778.

The 30th Annual Tucson Gem and Mineral Show will be held during February 9-12, 1984 at the Tucson Community Center. For further information, contact the Tucson Gem and Mineral Committee, PO Box 42543, Tucson, AZ 85733.

HELIUM RESOURCES AND PRODUCTION IN ARIZONA

by Jon E. Spencer

INTRODUCTION

Gas fields in Arizona yielded the world's *richest* known helium gas between 1960 and 1977. This helium-rich gas, occurring in the Pinta Dome, Navajo Springs, and East Navajo Springs gas fields near Holbrook in northeastern Arizona, contained about 8-10 percent helium mixed mostly with nitrogen. These gas fields are also somewhat unique because the helium is not mixed with hydrocarbons. The world's *largest* known helium reserves are natural gas fields containing less than one percent helium, and are located in Texas, Oklahoma, Kansas, and Wyoming. These enormous fields contain much greater volumes of helium than Arizona's gas fields, but the helium is more expensive to extract because of its lower concentration.

All known helium occurrences in the state are within the Colorado Plateau and adjacent to the Defiance uplift (Figure 1). Arizona's only *major* helium source is at the south end of the Defiance uplift. The helium reservoir rock is primarily the Permian Coconino Sandstone, although helium has also been reported from red sandstones near the base of the Chinle Formation, and from the upper part of the Pennsylvanian (?)-Permian Supai Formation (Dunlap, 1969; Peirce and others, 1970). A single well in Devonian and Mississippian strata at the north end of the Defiance uplift (Teec Nos Pos oil and gas field, Figure 1) has produced helium, and at present, natural gas containing several percent helium is being vented from a well in the Black Rock field near Teec Nos Pos.

GEOLOGY OF THE
PINTA DOME, NAVAJO SPRINGS, AND
EAST NAVAJO SPRINGS HELIUM FIELDS

The geology of the Pinta Dome, Navajo Springs, and East Navajo Springs helium fields is characterized by "layer cake" Colorado Plateau stratigraphy, with gentle warps of various sizes that locally produce structural traps for gas accumulation. Each helium field occurs within one of three domal structures separated by faults and closed structural contours. The helium and associated gases occur primarily in the porous Coconino Sandstone which is capped by impermeable shales of the lower part of the Moenkopi Formation. The following description of subsurface geology is based primarily on Dunlap's (1969) study of the area.

Stratigraphy

Lower Paleozoic strata are generally missing in and around the Defiance uplift; consequently, the Pennsylvanian (?)-Permian Supai Formation rests directly on Precambrian granitic crystalline rocks at a depth of approximately 3,000 feet (Figure 2).

The Supai Formation can be subdivided into three members: 1) a basal member composed of approximately 700 feet of siltstone and mudstone; 2) the middle Fort Apache Member, composed of 20-25 feet of dolomitic limestone; and 3) an upper member composed of about 1,000 feet of halite, gypsum, and anhydrite interbedded with shaley siltstone and mudstone. The upper evaporitic
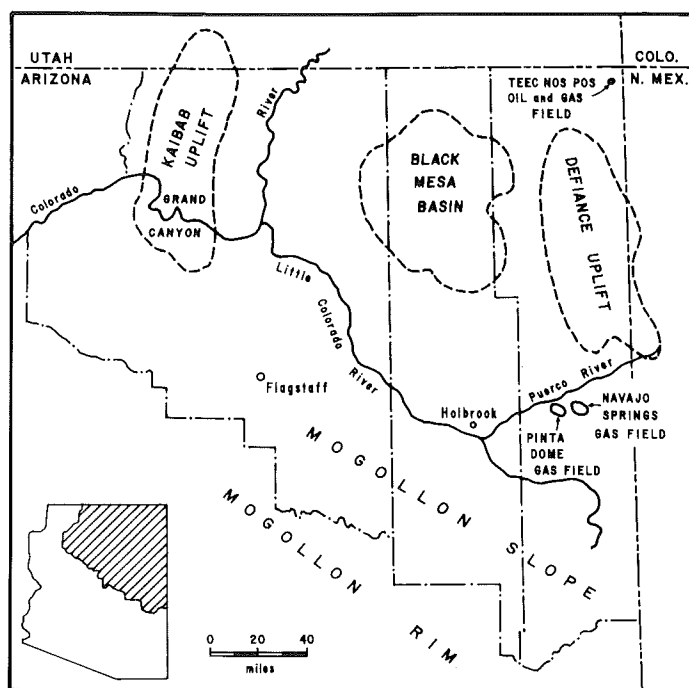

Figure 1. Index map of northeastern Arizona showing location of major geologic features (Dunlap, 1969).

member represents the northeast margin of the Holbrook basin.

The Lower Permian Coconino Sandstone is 250-325 feet thick in the helium-producing area and is composed of fine-to-medium-grained, porous and permeable quartz sandstone. Porosity is variable and may be as high as 20 percent. This rock is a productive aquifer, as well as the primary helium reservoir rock in the Holbrook area. The gas-bearing zone is in the upper part of the Coconino Sandstone, whereas middle and lower zones are generally water bearing.

Lower Triassic Moenkopi Formation rests disconformably on Coconino Sandstone, with normally intervening Kaibab Formation completely missing in the Holbrook area. The Moenkopi Formation is composed of variably calcareous siltstone, mudstone, and silty sandstone. Micaceous siltstone and silty mudstone at the base of the Moenkopi Formation form an impermeable cap, preventing upward escape of gas from the underlying Coconino Sandstone.

The Upper Triassic Chinle Formation unconformably overlies the Moenkopi Formation. The basal Shinarump Member consists of 10-60 feet of conglomeratic sandstone and is locally a helium-bearing zone. It is overlain by the lower red member (Akers and others, 1958), which is composed of about 50 feet of sandstone, sandy siltstone, and mudstone, and is also locally helium bearing. The overlying Petrified Forest Member is a sequence of mudstone, siltstone, claystone, sandstone, gypsum, and limestone. Only the basal 200 feet of this member is preserved in the helium-producing area.

The late Tertiary Bidahochi Formation, consisting of 0-180 feet of lacustrine and fluviatile sediments, unconformably overlies the Chinle in some areas around the

SYSTEM OR SERIES		FORMATION	THICKNESS	LITHOLOGIC CHARACTERISTICS
Quaternary				Alluvium, sand and gravel
		── UNCONFORMITY ──		
Tertiary		Bidahochi Formation	0-180	Grayish-brown calcareous sandstone interbedded with silty mudstone and volcanic ash; bentonitic
		── UNCONFORMITY ──		
Triassic	Upper	Chinle Formation	650-850	Reddish-brown to grayish-blue mudstone and claystone with some silty sandstone; some limestone and gypsum in upper portion; siltstone and conglomeratic sandstone in lower portion
		── UNCONFORMITY ──		
	Lower to Middle (?)	Moenkopi Formation	125-150	Brown to gray calcareous siltstone and mudstone; slightly gypsiferous; very silty
		── UNCONFORMITY ──		
Permian	Lower	Coconino Sandstone	250-325	Light gray to buff, fine- to medium-grained sandstone; loosely to firmly cemented with silica
		Supai Formation	1,700?	Reddish-brown sandstone, siltstone, and mudstone; some dolomitic limestone; thick interbedded evaporitic sequence in upper portion
Pennsylvanian (?)		── UNCONFORMITY ──		
Precambrian				Crystalline basement rocks

Figure 2. Generalized stratigraphy of sedimentary rocks exposed at the surface and encountered in the subsurface in the Pinta Dome-Navajo Springs area, Apache County, Arizona (Dunlap, 1969).

helium-producing area. In other areas, this formation has been removed by erosion and Chinle Formation is exposed at the surface. Quaternary sediments locally cover both formations.

Structure

The Pinta Dome, Navajo Springs, and East Navajo Springs helium fields occupy a broad structural saddle between the Defiance uplift to the north, and gently northeast-dipping

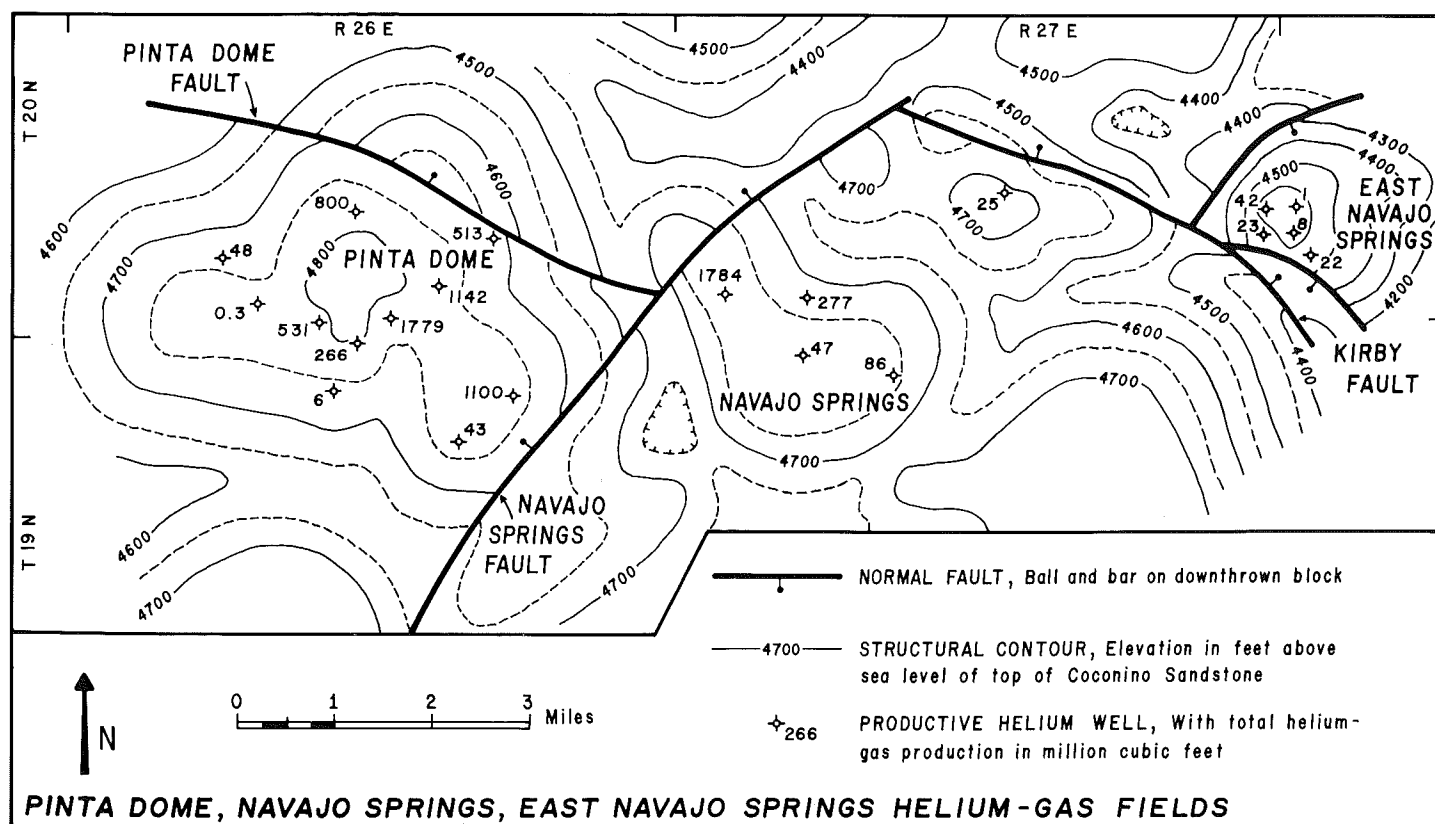PINTA DOME, NAVAJO SPRINGS, EAST NAVAJO SPRINGS HELIUM-GAS FIELDS

Figure 3. Structure-contour map of the top of the Coconino Sandstone in the subsurface in the Pinta Dome, Navajo Springs, East Navajo Springs area, Apache County, Arizona (Conley and Scurlock, 1976). Also shows location of productive helium-gas wells and amount of helium-gas produced from each gas well in this area (production data from Arizona Oil and Gas Conservation Commission, 1982).

EARTH FISSURES AND LAND SUBSIDEN

by Michael K. Larson and Troy L. Péwé

INTRODUCTION

Earth fissures—long, narrow, eroded tension cracks associated with land subsidence caused by ground-water withdrawal—have formed during the past 50 years in alluvial basins of southern and south-central Arizona (Leonard, 1929; Schumann, 1974; Laney, Raymond, and Winikka, C.W., 1978; Peirce, 1979; Jachens and Holzer, 1982). Until recently, the fissure hazard has been confined to outlying agricultural areas. In January 1980 a 400-foot-long fissure opened in Paradise Valley at a residential construction site of northeast Phoenix. This fissure is the first known occurrence in a densely populated, non-agricultural area of the state, and the first in the city of Phoenix.

Land subsidence and earth fissures pose serious problems for urban areas, with the potential for widespread damage to manmade structures. Well failure is a dramatic manifestation of subsidence as the casing collapses or the well head protrudes above the ground. Canals designed for gravity flow may overflow as a result of local sags and gradient reversals. Water and sewer mains that also depend on gravity flow may reverse flow or clog, and in extreme cases rupture, because of altered gradients. Subsidence may also necessitate new designs of storm drainage systems, and expensive, repeated levelings of benchmarks, resulting in obsolete surveying data. Fissures may directly damage buildings, roads, and other architectural structures. However, even without ground failure, differential subsidence in and of itself may cause damage to structures large in area or height.

Our recently completed study (Péwé and Larson, 1982) outlines in detail the problems of ground-water withdrawal, land subsidence, and earth fissuring in northeast Phoenix (Figure 1). The research consisted of a detailed gravity survey supplemented by geologic mapping, precise, re-

Figure 1. Map of Paradise Valley with study area outlined.

peated land surveying, and interpretation of well records. The city of Phoenix Engineering Department has provided logistical support, partial funding for the project, and has published the final report.

THE PHOENIX FISSURE

The fissure at 40th Street and Lupine Avenue opened 400 feet in an east-west direction, marked by hairline cracks, small open holes, and a linear opening 15 feet long, and as much as 8 feet deep and 15 inches wide (Figure 2). No vertical offset was observed; the fissure appeared to be an example of a tensional break. The crack appeared after locally heavy rains on the weekend of January 19, 1980. Such fissures have been commonly reported after rain showers or application of irrigation water, apparently because the cracks first open below the surface, only to be eroded later by downward percolation of the surface water. At the 40th Street construction site, the overlying soil cover had been scraped off, exposing the subterranean crack, and the collecting of rainwater in a retention basin eroded the large main cavity. The temporary halting of construction, modification of plans, hiring of consultants, and other expenses incurred as a result of the fissure are estimated by the owners of the subdivision to have cost them approximately $500,000.

HISTORY OF GROUNDWATER DEVELOPMENT AND LAND SUBSIDENCE

Water levels remained nearly constant in the study area prior to about 1950, generally within 250 feet of the surface. Increased pumpage in relatively unproductive aquifers has caused rapid water-level decline, particularly in two areas where ground-water has dropped more than 300 feet from its original level. These "cones of depression" are centered halfway between Greenway and Bell Roads at 44th Street and near 56th Street and Thunderbird Road. Withdrawals of ground water are many times the natural recharge rate, and this overdraft has resulted in depletion of thin aquifers peripheral to the mountains, and loss of supply to shallow wells. More wells will certainly become dry as pumping in the area continues.

Since the mid-50s, water levels have declined, resulting in current water depths of more than 500 feet. Subsidence apparently began about a decade later in the vicinity of 52nd Street and Thunderbird Road after water levels declined from 100 feet to 150 feet. Since 1970 the subsidence bowl has increased in size at an average rate of two square miles per year, with early expansion predominantly in a westerly direction, and more recent expansion toward the north and east.

As of March 1982, the maximum subsidence measured was 3.44 feet at 56th Street and Thunderbird Road (Figure 3), near the center of the southern cone of water-level depression. At the assumed center of the subsidence area (or subsidence "bowl") 0.5 miles to the southwest (Figure 3), there is indirect evidence from topographic and land survey data for as much as 5 feet of subsidence. Harmon (1982) noted that the subsidence rate has increased to the south, particularly at 56th Street and Cactus
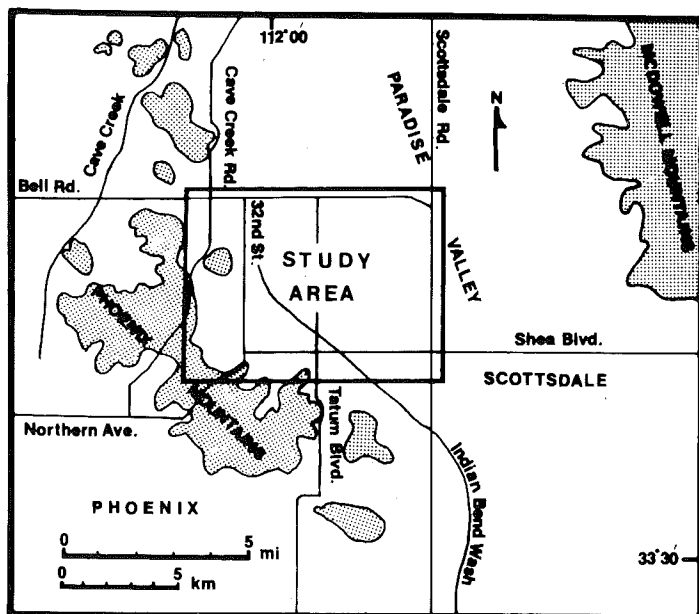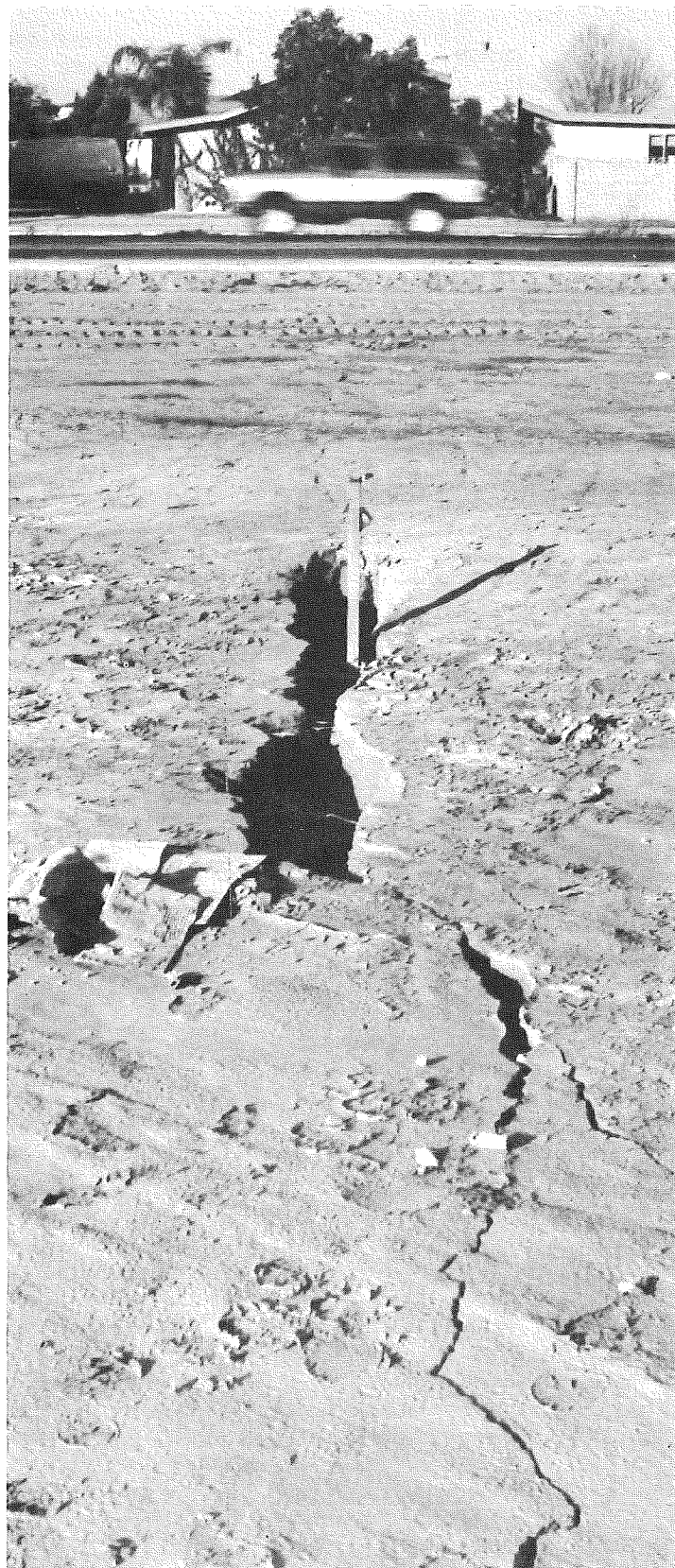
CE HAZARDS IN NORTHEAST PHOENIX

Figure 2. Earth crack in construction area at Lupine Avenue and 40th Street, Phoenix, Arizona. View is west toward 40th Street. Photo by Troy L. Péwé, No. 4484, January 27, 1980.

Road, and Tatum Boulevard and Cholla Street, where the ground is subsiding 4-5 inches per year. This occurrence may represent a southward shift in the center of the subsidence bowl.

The growth of the subsidence bowl suggests that it will expand farther, particularly toward the north and east; subsidence has been measured to the east in the city of Scottsdale. The extent of land subsidence to the south into the town of Paradise Valley, however, is not known. There is insufficent data on compaction and material properties of the subsurface to fully evaluate the potential of future land subsidence in northeast Phoenix; however, given known thicknesses of alluvium and present subsidence rates near the center of the subsidence bowl, more than 9 feet of land subsidence is possible if this area is completely dewatered.

The apparent lack of significant subsidence near the northern cone of depression of water levels may be due to the slow draining of the 200-foot-thick clay layer. Greater subsidence in this area will probably occur as water levels reach the base of the clay unit.

SUBSURFACE CONDITIONS

Well-drilling records and gravity data provide the basis for a depth to bedrock map (Figure 4). The map shows the relationship of past and potential land subsidence and earth fissuring to the buried bedrock topography.

The underground bedrock slopes gently toward the northeast from the Phoenix Mountains. The inner part of this area is buried less than 500 feet, and extends at least 2.5 miles into the Paradise Valley basin, with a series of hills and ridges with relief of 100-300 feet (Figure 4). The buried bedrock features follow the same NE-SW direction as the foliation and topographic expression in the adjacent Phoenix Mountains. One can visualize the buried bedrock topography as that which would exist if the present Papago Park (three miles SE of the Phoenix Mountains) were buried beneath 300-500 feet of silt, sand, and gravel.

Bordering the inner surface, is an outer, more deeply buried, low-relief topography, sloping gently northeast-ward at a depth of 500-1,000 feet. A major NW-SE basin and range fault separates this gently sloping surface from thick deposits of consolidated sediments.

The subsurface geologic conditions control patterns of water-level decline and land subsidence. Maximum subsidence and water-level decline have been on the deeper outer surface; whereas minimal subsidence and little or no water has been obtained from wells drilled on the shallow buried inner surface. Subsidence generally increases wherever the thickness of alluvium increases.

Gravity data indicate that a small bedrock hill underlies the fissure at a depth of about 150 feet, with at least 100 feet of relief (Figure 5C). Differential compaction induced by dewatering of sediments across this buried knoll was sufficient to cause ground failure. Continued differential subsidence has been measured (April 1981 to April 1982) along 40th Street between Shea Boulevard and Cactus Road, with as much as 0.17 feet of subsidence south of the fissure (Figure 5B). The striking similarity between the
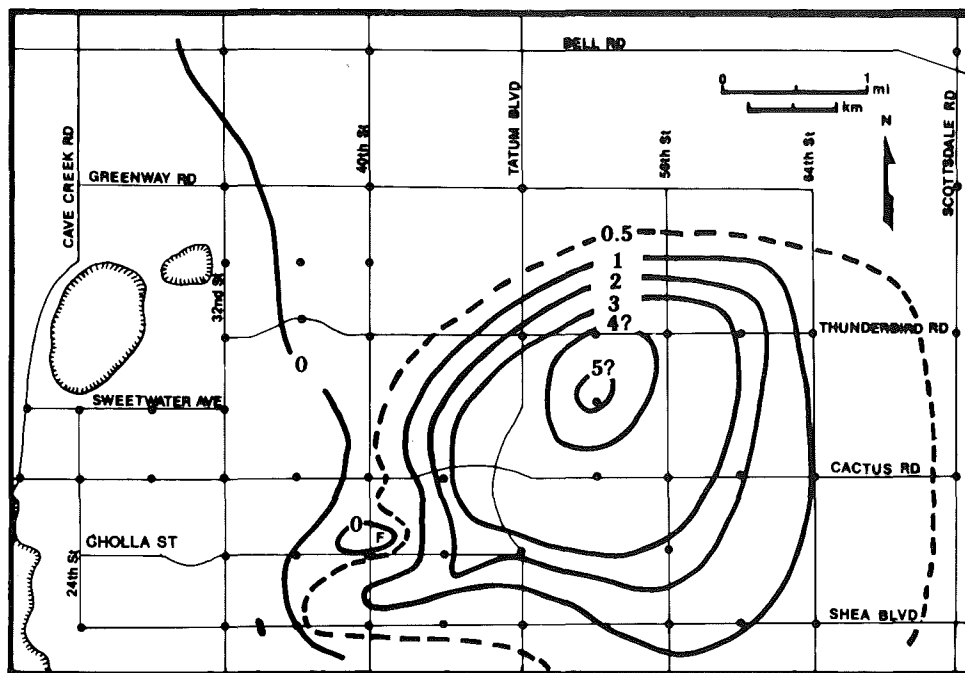
Figure 3. Land subsidence (in feet), northeast Phoenix from 1962-1982. "F" indicates location of fissure. Dots indicate locations of city benchmarks.

subsidence curve and an interpreted depth-to-bedrock profile along 40th Street supports the argument that fissuring is associated with the crests of buried hills. On the basis of the subsidence profile, theoretical calculations and computer modeling by Michael Larson (Figure 5A) and Dr. Donal Ragan at Arizona State University Department of Geology indicate that the stress in the sediments over the inferred buried hill was sufficient to crack the ground surface in 1980.

Measured differential subsidence and calculated horizontal strain strongly suggest a reopening of the entire fissure. Continued displacement is indicated by small cracks that have lengthened and become more numerous in the newly constructed paved road and concrete wall across the original fissure trace. On the basis of detailed

Figure 4. Estimated depth to bedrock (in feet) and potential fissure areas, northeast Phoenix. Contour interval 200 feet.

gravity traverses, a future westward extension of the fissure is probable, with less than 600 feet of eastward extension possible. Several fissures subparallel to the original could form in the vicinity of 40th Street and Lupine Avenue.

The history of fissured basins in southern Arizona bears ample evidence that the initial fissure is later followed by complex patterns of multiple fissuring. In northeast Phoenix, future fissuring may be localized in three geological settings: 1) buried bedrock topographic highs, 2) at the hinge line of subsiding areas controlled by bedrock depth, and 3) buried fault scarps. Gravity data suggest there are several buried hills between 30th and 42nd Streets, with a high probability of fissuring, particularly near those hills directly north of the fissure (Figure 4). Another area of potential fissuring is near the hinge line of subsidence between Shea Boulevard and the Phoenix Mountains east of 34th Street. Differential subsidence and fissuring are also possible across an inferred buried basin and range fault scarp in the eastern part of the study area; however, because most water-level decline and land subsidence has occurred on the upthrown rather than the downthrown fault block, fissuring seems less likely in this area at the present time.

CONCLUSIONS

Studies such as that of the northeast Phoenix area permit a better understanding of earth fissures and land subsidence phenomena. Hydrogeological and geophysical methods are now available to delimit specific areas where there is a high potential for problems due to fissuring and land subsidence. Many of these methods have been applied to the northeast Phoenix study, but as land subsidence and water-level decline continue, ongoing monitoring is necessary in order to anticipate future problems.

Similar studies could prove timely elsewhere in south central Arizona, because of the widespread distribution of ground-water development in similar geologic settings. Cooperation of city, state, and federal governments and
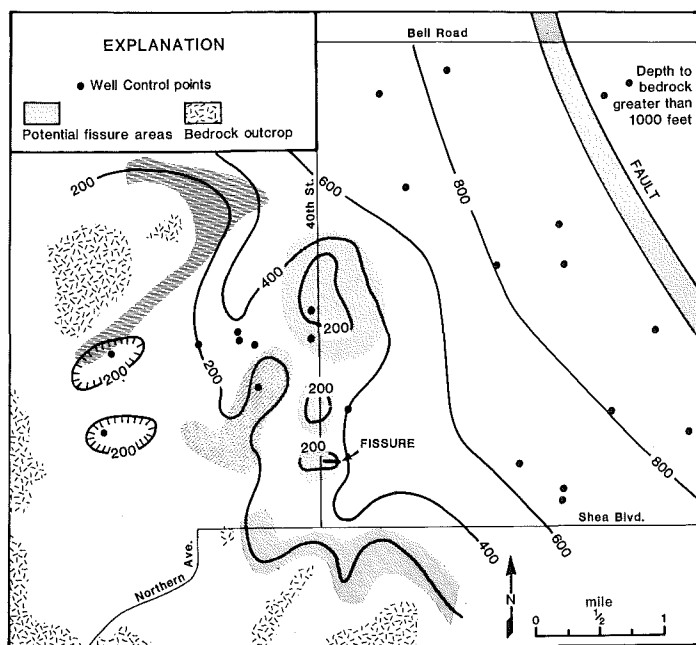
public education is essential if problems associated with water-level decline, land subsidence, and earth fissures are to be resolved.

For a copy of the report, make checks payable for $25.00 ($26.00 if mailed) to the City of Phoenix. Requests are taken by David Harmon, Assistant City Engineer, City of Phoenix Engineering Department, 125 East Washington St., Phoenix, AZ 85004.

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KRAKATAU—A Geologic Cataclysm

One hundred years ago, on August 27, 1883, the island of Krakatau exploded; then, after several days, it disappeared into the Sunda Strait near Java and Sumatra. A volcano, dormant for 203 years, had erupted, causing the two-mile-long island to collapse into the sea. All that remained after the explosion was a caldera or basin, five miles wide and more than 700 feet deep.

The volcanic blast, equal to 100-150 megatons of explosives, was heard 3,000 miles away. Seismic waves traveled several times around the earth in both directions. Four cubic miles of ash and pumice was spewed into the atmosphere (about 60 times the ejecta produced by Mount St. Helens during the early 1980s). Two islands adjacent to Krakatau were covered by 45 feet of ash and pumice, then overlain by 180 feet of lava. The heavier fallout ash blanketed 180,000 square miles; the airborne ash drifted in the stratosphere for many months, causing vivid sky scapes around the world. A sulfate/dust layer remained in the atmosphere for over five years, combining with ozone and precipitation to create a 'greenhouse' effect. As a result, a portion of solar heat was prevented from reaching the surface of the earth, and lower average surface temperatures occurred.

Loss of life from the eruption and the accompanying tsunami (the great sea wave that destroyed 300 villages and thousands of ships) is estimated to have been between 36,000 and 100,000 people.

Just as the mythical Phoenix arose from its own ashes, Anak Krakatau (child of Krakatau) first emerged as a new cone in 1927, and has since produced 30 small eruptions. Anak Krakatau is one of 500 known active volcanoes in the world today. Three of the six worst volcanic disasters in the world since the beginning of the 16th century have occurred in Indonesia (Kelut in 1586, Tambora in 1815, and Krakatau in 1883). In order of the most active volcanic history, Indonesia ranks first, Japan, second, and the United States, third.

ANNOUNCEMENT

Daniel N. Miller, Jr., resigned from his position as Assistant Secretary for Energy and Minerals at the Department of the Interior at the end of May 1983. He had occupied that position since May 1981.

In his capacity as Assistant Secretary, Miller headed up the U.S. Geological Survey, the U.S. Bureau of Mines, the Office of Surface Mining, and most recently, the Minerals Management Service.

Prior to joining Secretary Watt's team, Miller served 12 years as State Geologist of Wyoming and Director of the Wyoming Geological Survey. He also spent 11 years as Senior Exploration Geologist in the petroleum industry.

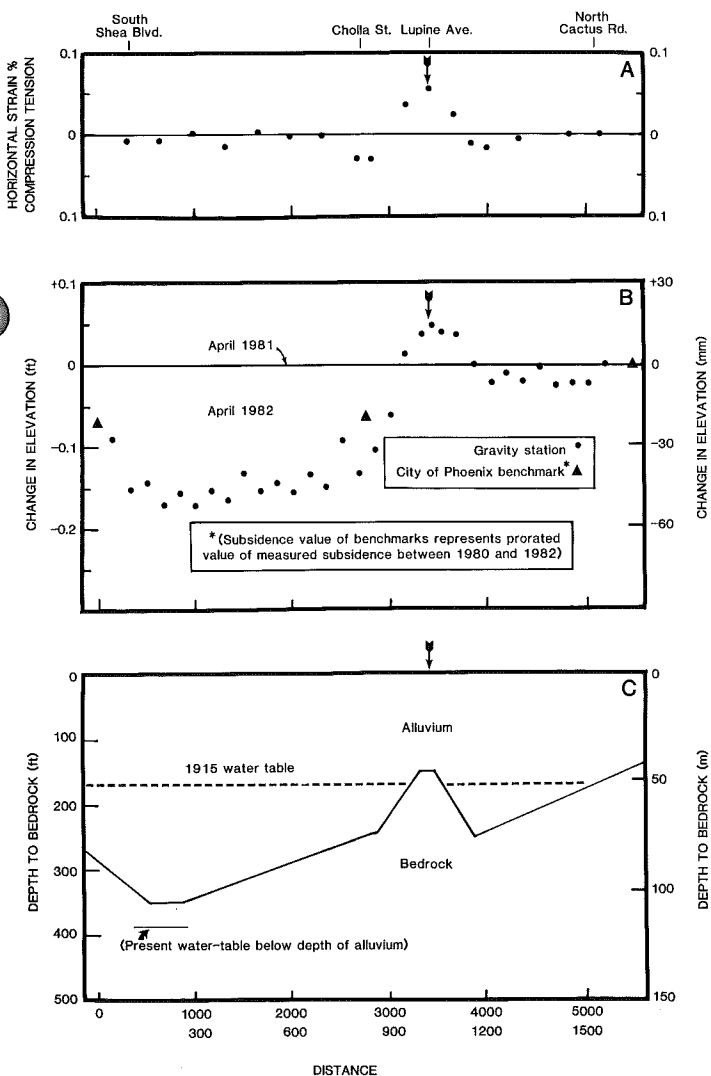Miller will reside in Coeur d'Alene, Idaho, where he will establish a consulting service.

Figure 5. Surface strain, land subsidence, and depth to bedrock, 40th Street from Shea Boulevard to Cactus Road.

5A. Computed horizontal surface strain (1980) at time of fissuring.

5B. Land subsidence from April 1981 to April 1982.

5C. Interpreted depth to bedrock based on gravity data.

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77-1   Map of published Phanerozoic age determinations in Arizona, 1977, Keith, S.B., and Reynolds, S.J., scale 1:1,000,000 (Geological Survey Branch). $1.50

77-1a   Compilation of radiometric age dates for Arizona, 1977, Keith, S.B., 187 p. (Geological Survey Branch). $14.50

77-2   Landsat lineament map of Arizona with emphasis on Quaternary fractures, 1977, Lepley, L.K., scale 1:1,000,000, 30 p. (Geothermal Assessment Project). $6.25

78-1   Low-temperature geothermal reservoir site evaluation in Arizona, 1978, Hahman, W.R., 128 p. (Geothermal Assessment Project). $11.50

78-2   Quarterly progress report for period May 1, 1977-Jan. 31, 1978, 1978, Hahman, W.R., 57 p. (Geothermal Assessment Project). $8.00

78-3   The geology of Arizona: its energy resources and potential, 1978, Nations, Dale, *in* The Interstate Oil Compact Commission Committee Bulletin, v. xx, no. 2, p. 42-53. $1.50

78-4   Skylab lineament map of Arizona with tectonic model and exploration guide for geothermal resources, 1978, Lepley, L.K., 10 plates, scale 1:500,000, 35 p. (Geothermal Assessment Project). $20.50

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79-2   Geothermal reservoir site evaluation in Arizona, semiannual progress report for the period July 15, 1978-Jan. 15, 1979, 1979, Hahman, W.R., 91 p. (Geothermal Assessment Project). $9.50

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†Report not available through mail.

*Report available from Dr. D.H. White, Department of Chemical Engineering, University of Arizona, Tucson, AZ 85721.

79-6 Geothermal energy in Arizona (excerpt from Geothermal Energy, v. 7, no. 11), 1979, Hahman, W.R., p. 7-18 (Geothermal Assessment Project). $1.50

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*79-8 Geothermal development plan, Maricopa County, 1982, Goldstone, L.A., and White, D.H., 64 p. (Geothermal Commercialization Project, Department of Chemical Engineering, University of Arizona).

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†79-12 Preliminary geothermal assessment of the Willcox Basin, 1979, Jones, N.O., and Campbell, Alice, 33 p., seven plates (Geothermal Assessment Project).

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81-22   Preliminary detailed geologic map and cross sections of the Clifton Hot Springs and San Francisco River area, 1981, Cunningham, J.E., two maps, scale 1:24,000 (Geothermal Assessment Project). $2.50

†81-23   Report on the reconnaissance resistivity and VLF-EM surveys of the Safford Valley area, Graham County, Arizona, 1981, Phoenix Geophysics Inc., 10 figures, 15 plates, 14 p. (Geothermal Assessment Project).

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81-26   Geothermal resource potential of the Safford-San Simon basin, Arizona, 1981, Witcher, J.C., 131 p., four plates (Geothermal Assessment Project). $14.00

†81-27   Feasibility study for geothermal water space heating for the Safford Federal Prison Camp, Safford, Arizona, 1981, Johannessen and Girard Consulting Engineers, Inc., 55 p.

81-29   Preliminary assessment of the geothermal potential—City of Scottsdale, Paradise Valley, Maricopa County, Arizona, 1981, Stone, Claudia, 43 p. (Geothermal Assessment Project). $6.50

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†82-9   Origin of ground subsidence and earth fissures, northeast Phoenix, Arizona, 1982. Péwé, T.L., and Larson, M.K., with appendix, 169 p. (City of Phoenix).

*82-10   Executive summary: the potential of utilization of geothermal energy in Arizona, 1982, White, D.H., and Goldstone, L.A., 52 p. (Geothermal Commercialization Project, Department of Chemical Engineering, University of Arizona.

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Helium Resources continued

strata of the Mogollon slope to the south and southwest (Figure 1). The saddle separates the structurally lower Black Mesa Basin to the northwest from a structural low to the southeast that may be part of the Gallup sag (Peirce and others, 1970). Within this regionally defined saddle are a number of smaller uplifts of low relief, some of which form traps for helium accumulation. The geometry of subsurface structures in the helium-producing area is known primarily from drill hole data (Dunlap, 1969; Peirce and Scurlock, 1972; Conley and Scurlock, 1976).

The Pinta Dome helium field occurs within the Pinta anticline, an east-west-trending, doubly plunging structure with about 100 feet of relief (Figure 3). Dips on the flanks of Pinta Dome are typically 0.5-1.5 degrees. The Pinta Dome fault offsets the northeast flank of the dome.

A northwest-trending anticline about three miles east of Pinta Dome forms the Navajo Springs helium field. This doubly plunging anticlinal structure has about 100 feet of structural relief, and is terminated northward by the Navajo Springs fault. The small East Navajo Springs helium gas field, about five miles east of the Navajo Springs field, lies immediately northeast of the Kirby fault (Figure 3).

ORIGIN OF HELIUM

Terrestrial helium has two sources: 1) primordial helium that was incorporated into the Earth at the time of its formation and is now derived from sources deep within the Earth, and 2) radioactive decay of uranium and thorium which are concentrated in the Earth's crust. Helium is composed of two isotopes: helium 4, which is produced by radioactive decay, and helium 3, which was created before the Earth formed and was incorporated into the Earth during its formation. High ratios of helium 3 to helium 4 in some hot springs associated with volcanic activity indicate the presence of a significant component of primordial helium probably derived from the mantle. Low ratios of helium 3 to helium 4 found in most, if not all, natural gas fields, indicate that this helium was primarily derived from radioactive decay of uranium and thorium.

The Coconino Sandstone contains very little uranium and thorium, and consequently could not be a significant source of helium in the Pinta Dome-Navajo Springs area. One possible source for the helium is the Precambrian crystalline basement beneath the sediments (Peirce and Scurlock, 1972). There is little information on the detailed nature of these rocks, but they include granitic rocks that likely contain small amounts of helium-producing radioactive elements. A problem with this potential source is that the Supai Formation, separating crystalline basement from Coconino Sandstone, contains hundreds of feet of impermeable evaporites. However, Supai evaporites wedge out rapidly to the northeast and northwest. Helium originating from the Precambrian basement could have migrated upward to the Coconino Sandstone where Supai evaporites are absent, and then migrated up-dip through Coconino Sandstone to structural traps above evaporitic Supai sediments. The presence of helium in clastic sediments between Supai evaporites may also result from up-dip lateral migration from evaporite-free areas. Fracturing may also permit upward migration of helium through evaporitic strata (Peirce and others, 1970).

Alternatively, helium may have originated from sediments overlying the Coconino Sandstone. Gamma ray logs from drill holes indicate that the Shinarump and Petrified Forest Members of the Chinle Formation, and the lower part of the Moenkopi Formation, contain significant amounts of radioactive material. In most areas, helium from these possible helium-source rocks would have had to migrate downward through relatively impermeable strata to reach the Coconino Sandstone. However, faulting has locally brought these potential helium-source rocks down and into contact with the reservoir rocks, perhaps eliminating this access problem (Dunlap, 1969).

HELIUM PRODUCTION IN ARIZONA

In 1961 Kerr McGee Corporation and Eastern Petroleum began production of helium from the Pinta Dome field near Holbrook, and opened the world's first commerical helium extraction and purification plant. The Navajo Springs and East Navajo Springs helium fields began production in 1964 and 1969, respectively. One well in the Teec Nos Pos oil and gas field produced helium during 1968 and 1969. Production of helium gas from all these fields ended by 1976 because the gas fields had either been depleted or had become unprofitable due to a large drop in helium prices. No helium has been produced in Arizona since this time (Figure 4).

Statistics compiled by the Arizona Oil and Gas Conservation Commission indicate that Arizona's gross helium gas production has been 9,238 million cubic feet, almost all of which came from the Pinta Dome-Navajo Springs area. Assuming an average helium content of 8.5 percent, about 785 million cubic feet of helium was produced from Arizona, valued at an estimated $27 million (based on the 1961 price of $35 per thousand cubic feet; U.S. Bureau of Mines, 1980).* This amount of production is comparable to the total annual world helium consumption during the early 1970s.

*The 1980 government price (average value) for helium was $35 per thousand cubic feet; the 1980 private industry price was $22.50 (U.S. Bureau of Mines, 1980).

Figure 4. Annual helium production from helium-gas fields in Arizona (data from Arizona Oil and Gas Conservation Commission).
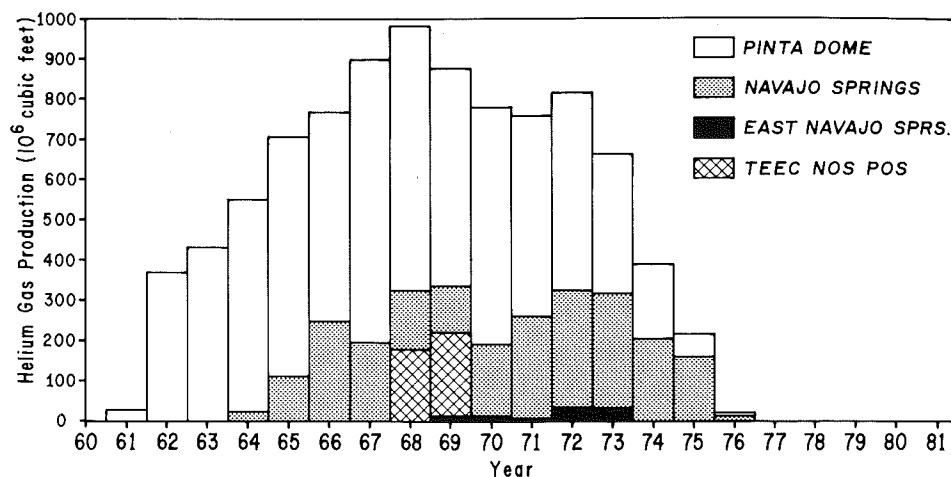
FUTURE OF ARIZONA'S HELIUM INDUSTRY

If crystalline rocks of the Defiance uplift are the source of the helium in the Pinta Dome and related helium-gas fields, then many other areas around the Defiance uplift may be promising targets for helium exploration. Much of the area around the Defiance uplift is within the Navajo Indian Reservation, and has had little, if any, exploration for helium. Wells drilled for helium exploration in this area generally penetrate only to the top of the Coconino Sandstone, although helium has also been reported from the underlying Supai Formation. It thus seems probable that other helium deposits await discovery in Arizona.

The cost of extracting helium from natural gas containing about 0.5 percent helium is about $13 per thousand cubic feet. Arizona helium can be extracted for significantly less since its concentration is much higher.

Natural gas reserves are being depleted at such a rapid rate that, if present trends prevail, there will be very little helium gas left within 30-40 years. When the demand for helium first exceeds the supply from natural gas, demand can be met with helium now in the federal storage reservoir. However, even this will run out eventually. When both natural gas reserves and the federal storage reservoir are depleted, the value of helium may increase a hundred to a thousand times. At such prices, the smallest helium gas fields would become highly valuable, and the Arizona helium industry could suddenly recover from decades of inactivity.

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